

Charmonia and exotics from BESIII

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Several states that couple to one light-meson and a heavy-charmonium are recently reported, including the $Z_c(3900)$ and $Z_c(4020)$. These states cannot be interpreted within the constituent quark-model of mesons, and are good candidates for a new form of quark matter, four-quark matter. A review of recent results on new charmonium-like states studied at BESIII is presented.

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1 Introduction

The quark model [1], which treats mesons as combinations of one quark and one anti-quark, is very successful in describing meson properties, particularly in the charmonium ($c\bar{c}$) region below the open-charm threshold. [2]. However, within the QCD and strongly coupled gauge theories [3], we can expect structures that are more than just $q\bar{q}$ combinations. Recent discoveries of heavy-flavor mesons [4] that do not fit into this simple quark-anti-quark picture, labeled XYZ , has inspired particle physics community to intensify studies to understand the nature and properties of these states.

2 Z-states studied by BESIII

The BESIII experiment was first to report the $Z_c(3900)$ state [5] in the $\pi J/\psi$ final state, and soon the $Z_c(4020)$ [6] was observed in the πh_c decays. Both of these states were discovered as charged particles, coupled to a pion and charmonium, making them four-quark ($u\bar{d}c\bar{c}$) meson candidates. However, both states have been also reported in respective neutral modes, thus complementing the isospin-triplet representation of isospin one, $I = 1$, resonances. As these two states are close to $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds, respectively, new structures coupling to two charmed mesons were soon discovered. The BESIII experiment is collecting more data in the XYZ region, to map the properties and decay modes of newly discovered states.

2.1 $Z_c \rightarrow \pi J/\psi$

Figure 1 shows the $Z_c(3900)^\pm$, identified in $\pi^\pm J/\psi$ decays (left), found in the reaction $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at the center-of-mass energy, $E_{CM} = 4.26$ GeV, using a 525 pb^{-1} data sample [5]. The plot on the right shows its isospin-partner, $Z_c(3900)^0 \rightarrow \pi^0 J/\psi$, found in the reaction $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$, at three energy points: $E_{CM} = 4.23, 4.26$, and 4.36 GeV, with respective luminosities of $1097.1, 825.7$ and 539.8 pb^{-1} [7]. The mass and width of the $\pi J/\psi$ structure in each case is determined from the fit, using a Breit-Wigner (BW) line shape combined with a non-resonant background contribution. Table 1 lists corresponding masses and widths.

2.2 $Z_c \rightarrow \pi D\bar{D}^*$

The $Z_c(3900)$ is close to the threshold for producing two charmed mesons, D and \bar{D}^* . Using a 525 pb^{-1} data sample collected at $E_{CM} = 4.26$ GeV, BESIII studied the processes $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\pm$, in which one charged pion and one D meson are identified, requiring that the missing mass is consistent with a \bar{D}^* [8], in so-called single D-tag procedure (ST). Resulting mass distributions of $D\bar{D}^*$ pairs are shown in

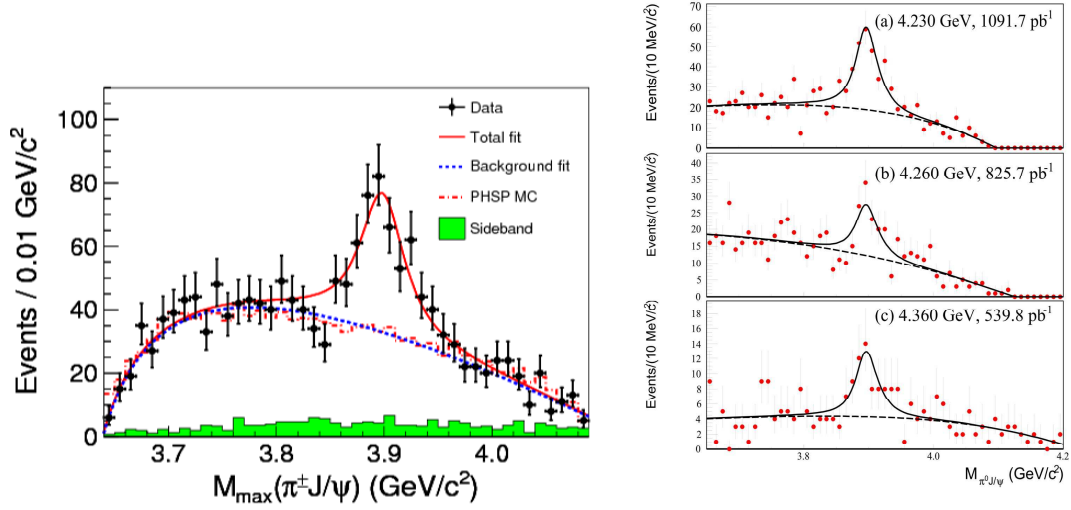


Figure 1: $Z_c(3900) \rightarrow \pi J/\psi$ production in $e^+e^- \rightarrow \pi\pi J/\psi$ processes. The left plot shows charged channels [5], while the neutral mode [7] is shown by the right plot.

Figure 2. In both decay channels, structures that cannot be explained by underlying background are evident, which we labeled as $Z_c(3885)$.

Using data samples collected at $E_{CM} = 4.23$ and 4.26 GeV, with respective luminosities of 1092 and 826 pb^{-1} , BESIII studied the same reaction with the requirement that both charmed mesons are fully reconstructed [9], in a double D-tag (DT) analysis. Resulting mass distributions, shown in Fig. 3, exhibit the same features observed in the ST analysis. The pole positions, extracted from mass-dependent BW-line shapes are provided in Table 1, where one can see that the DT-procedure reduced the errors. The mass difference with respect to the $Z_c(3900)$ falls outside the error boundaries, indicating that the $Z_c(3885)$ and $Z_c(3900)$ might be different objects. Angular analysis, favor the spin-parity assignment of $J^P = 1^+$ for this structure, in both ST and DT procedures.

2.3 $Z_c \rightarrow \omega\pi$

BESIII also searched for the production of Z_c states in the reaction $e^+e^- \rightarrow \omega\pi^+\pi^-$ at $E_{CM} = 4.23$ and 4.26 GeV [10]. Fig. 4 shows the $\omega\pi^\pm$ mass distribution, at $E_{CM} = 4.23$ GeV (left) and at $E_{CM} = 4.26$ GeV (right). There is no significant $Z_c(3900) \rightarrow \omega\pi$ signal, and the upper limits on the Born cross section are determined to be 0.26 and 0.18 pb, at $E_{CM} = 4.23$ and 4.26 GeV, respectively.

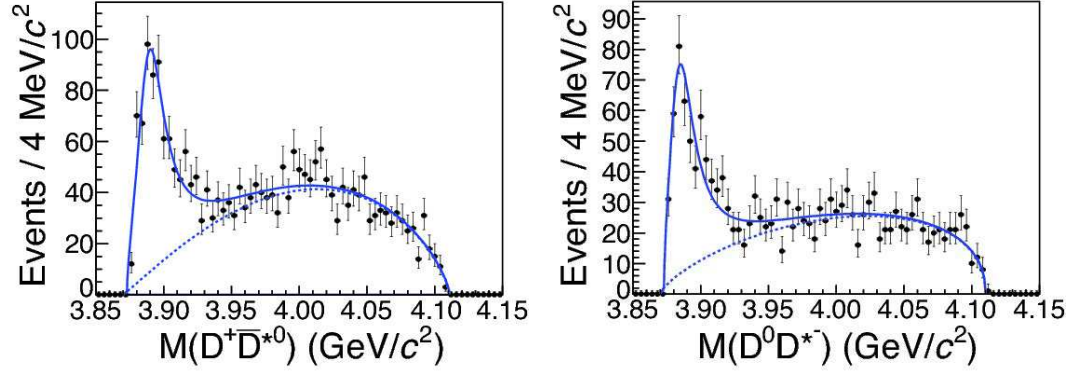


Figure 2: Structures identified as $Z_c(3885) \rightarrow D\bar{D}^*$ when one charmed meson is found [8] are evident.

2.4 $Z_c \rightarrow \pi h_c$

BESIII analyzed the reaction $e^+e^- \rightarrow \pi^+\pi^-h_c$, at $E_{CM} = 4.23, 4.26$ and 4.36 GeV [6]. Corresponding $\pi^\pm h_c$ invariant mass distribution, when all energy points are combined, is shown by the left plot of Fig. 5. The $Z_c(4020)^\pm$ signal has 8.9σ significance, and the inset represents a search for the $Z_c(3900) \rightarrow \pi h_c$, at $E_{CM} = 4.23$ and 4.26 GeV.

BESIII investigated the reaction $e^+e^- \rightarrow \pi^0\pi^0 h_c$, at $E_{CM} = 4.23, 4.26$ and 4.36 GeV [11]. The right plot in Fig. 5 shows the evidence for the neutral partner of the $Z_c(4020)^\pm$, in the mass distribution of a recoiling π^0 . Each structure, observed in the charged and neutral mode, is assumed to have a BW-line shape, and resulting masses and widths are given in Table 1. In the case of the $Z_c(4020)^0$ fit, the width is fixed to the value obtained analyzing charged decays.

2.5 $Z_c \rightarrow t_0 D^* \bar{D}^*$

Similarly to the case of the $Z_c(3900)$, the mass of the $Z_c(4020)$ is near the threshold for $D^*\bar{D}^*$ production. BESIII studied two reactions: $e^+e^- \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp$, at $E_{CM} = 4.26$ GeV [12], and $e^+e^- \rightarrow (D^*\bar{D}^*)^0 \pi^0$, at $E_{CM} = 4.23$ and 4.26 GeV [13]. The respective luminosities at two energy points are 1092 and 826 pb^{-1} . Fig. 6 shows the π^- (left) and π^0 (right) recoil mass distributions. A structure that couples to $D^*\bar{D}^*$ is evident, in both charged and neutral decays. The mass and width are extracted in each case using a BW-line shape, and corresponding values are listed in Table 1. The difference in values with respect to the $Z_c(4020)$, which couples to πh_c , warrants labeling this structure as a separate state: $Z_c(4025)$.

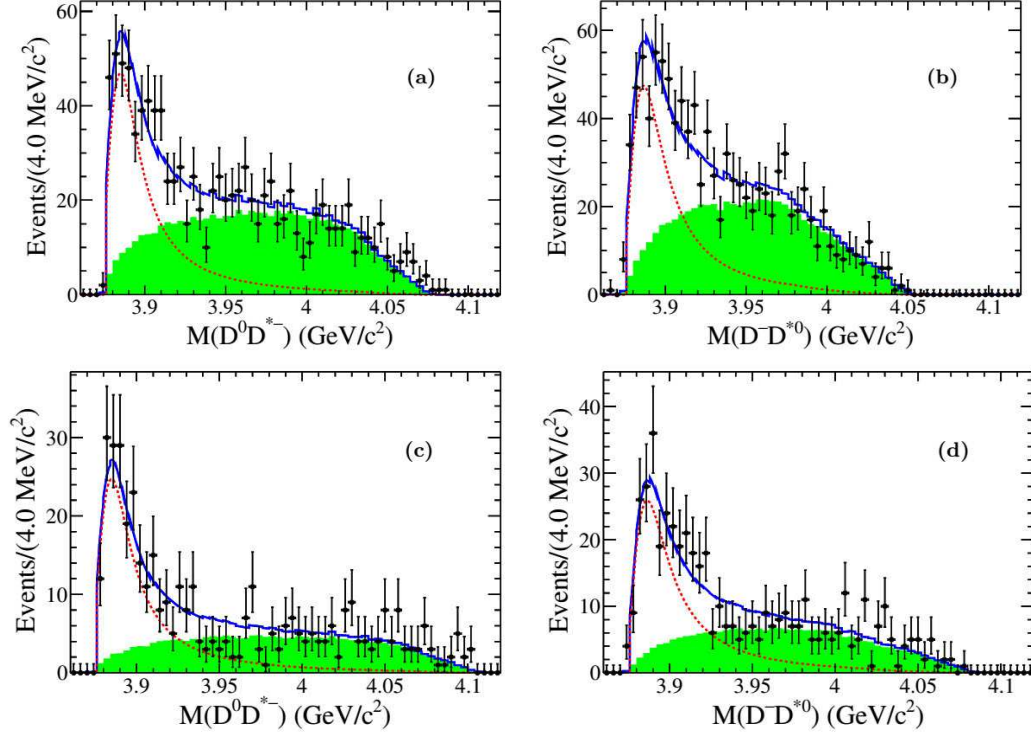


Figure 3: $Z_c(3883) \rightarrow D\bar{D}^*$ structures that were evident when one D -meson is found, Fig. 2, are also present when both D mesons are identified [8]. Top plots are obtained at $E_{CM} = 4.23$ GeV, while bottom plots correspond to $E_{CM} = 4.26$ GeV.

3 Relation between XYZ states

Two notorious meson candidates that do not fit into the quark-anti-quark model are $X(3872)$ and $Y(4260)$, discovered by Belle [14] and BaBar [15], respectively. BESIII is also able to investigate their properties, by looking into the reaction $e^+e^- \rightarrow \gamma\pi^+\pi^-J/\psi$ in the energy region between 4.2 and 4.6 GeV. Fig. 7 shows the invariant mass of $\pi^+\pi^-J/\psi$ candidates (left) where a clear $X(3872)$ signal can be seen. The right plot shows the cross section as a function of energy, compared with the line shape of the $Y(4260)$ production [16]. This plot indicates that there is a connection between the two states: $Y(4260) \rightarrow \gamma X(3872)$, which has not been reported before. BESIII is also looking into possible connections between the $Y(4260)$, and other Y states, to Z_c particles.

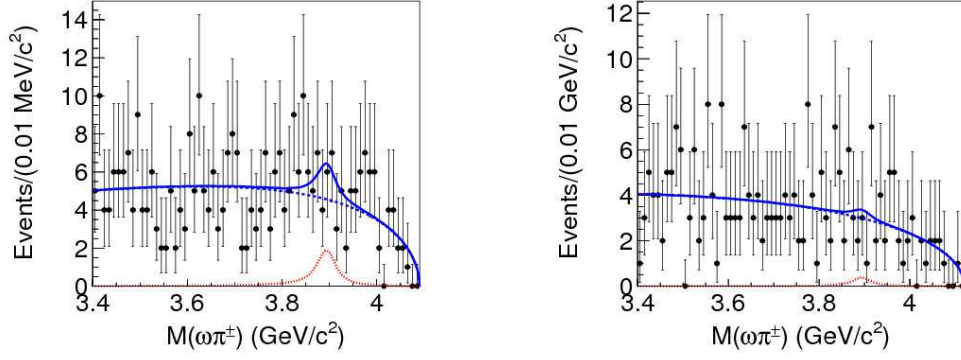


Figure 4: $\omega\pi$ mass spectra, obtained from the reaction $e^+e^- \rightarrow \omega\pi^+\pi^-$ at two energy points: $E_{CM} = 4.23$ GeV (left) and $E_{CM} = 4.26$ GeV (right) [10].

Decay	Mass [MeV/ c^2]	Width [MeV]	Ref.
$Z_c(3900)^\pm \rightarrow \pi^\pm J/\psi$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	[5]
$Z_c(3900)^0 \rightarrow \pi^0 J/\psi$	$3894.8 \pm 2.3 \pm 3.2$	$29.6 \pm 8.2 \pm 8.2$	[7]
$Z_c(3885)^\pm \rightarrow (D\bar{D}^*)^\pm$ (ST)	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$	[8]
$Z_c(3885)^\pm \rightarrow (D\bar{D}^*)^\pm$ (DT)	$3881.7 \pm 1.6 \pm 2.1$	$26.6 \pm 2.0 \pm 2.3$	[9]
$Z_c(4020)^\pm \rightarrow \pi^\pm h_c$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	[6]
$Z_c(4020)^0 \rightarrow \pi^0 h_c$	$4023.9 \pm 2.2 \pm 3.8$	fixed	[11]
$Z_c(4025)^\pm \rightarrow (D^*\bar{D}^*)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	[12]
$Z_c(4025)^0 \rightarrow (D^*\bar{D}^*)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	[13]

Table 1: Masses and widths of exotic meson candidates studied by BESIII.

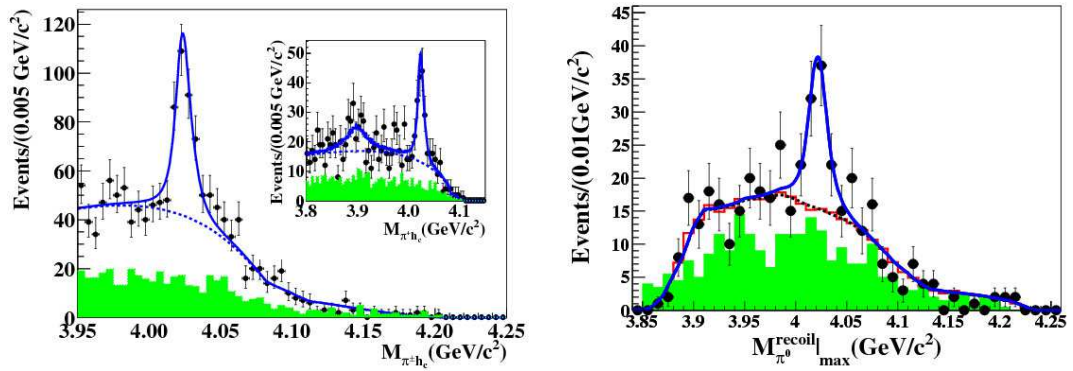


Figure 5: Production of the $Z_c(4020) \rightarrow \pi h_c$ in $e^+e^- \rightarrow \pi\pi h_c$ processes, at $E_{CM} = 4.23, 4.26$, and 4.36 GeV, evident in charged [6] (left) and neutral [11] (right) modes. The inset shows a fit that assumes the $Z_c(3900) \rightarrow \pi h_c$ production, at $E_{CM} = 4.23$ and 4.26 GeV.

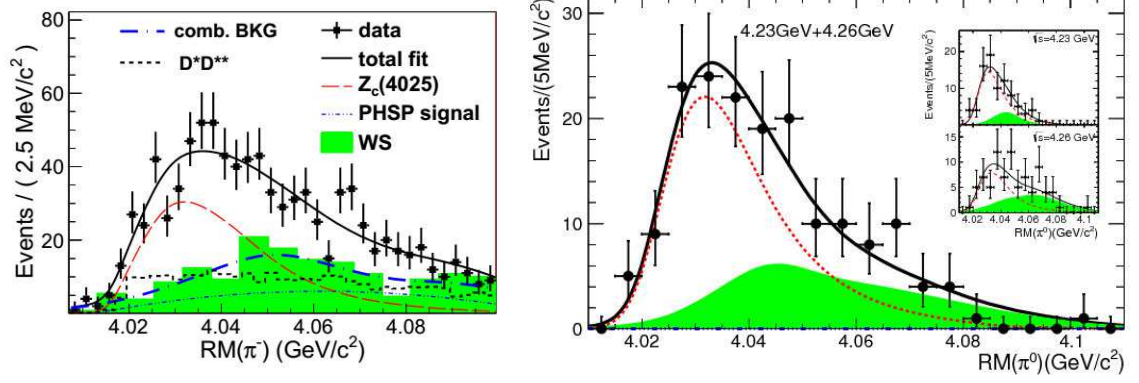


Figure 6: Production of the $Z_c(4025) \rightarrow (D^* \bar{D}^*)^\pm$ in the process $e^+e^- \rightarrow \pi^\pm (D^* \bar{D}^*)^\mp$, at $E_{CM} = 4.26$ GeV [12] (left). The $Z_c(4025) \rightarrow (D^* \bar{D}^*)^0$ signal can be observed in the right plot, obtained in the process $e^+e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0$, at $E_{CM} = 4.23$ and 4.26 GeV [13].

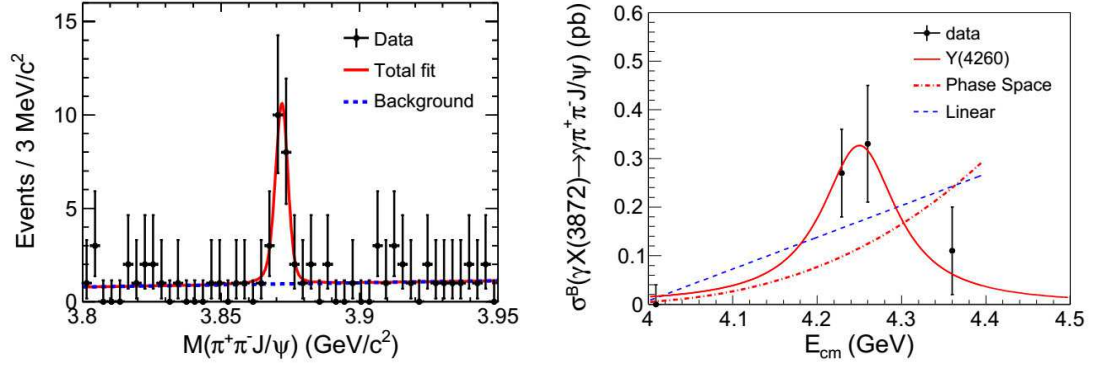


Figure 7: $X(3872)$ identified in the $\pi^+\pi^- J/\psi$ decays (left). The cross section for the reaction $e^+e^- \rightarrow \gamma \pi^+\pi^- J/\psi$ as a function of energy (right) [16].

4 Summary

BESIII is making progress in shedding light on properties of newly discovered exotic meson candidates. Two states that BESIII observed decaying to two different pion-charmonium combinations, namely the $Z_c(3900)$ and $Z_c(4020)$, are both established as isospin triplets. There are also two structures that couple to DD^* and D^*D^* pairs, namely the $Z_c(3885)$ and $Z_c(4025)$. It is possible that these are the same objects as the $Z_c(3900)$ and $Z_c(4020)$, respectively, because of their proximity to corresponding DD -thresholds. In addition, the $Z_c(4025)$ is also established as an isospin triplet, and BESIII is looking for the neutral partner of the $Z_c(3885)$. The spin analysis is also needed in order to establish, for example, that the $Z_c(3900)$ is the same as the $Z_c(3885)$. The evidence for the $Z_c(3900) \rightarrow \pi h_c$ and $Z_c(3900) \rightarrow \omega\pi$ decays is weak. However, BESIII observed the production of the $X(3872)$, in a process that is consistent with the radiative transition: $Y(4260) \rightarrow \gamma X(3872)$, something that has not been observed before. Hopefully, all this information should help theorists working on providing explanations for these intriguing meson structures.

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